

where  $W_{\text{net,out}}$  is the net work output of the heat engine,  $Q_H$  is the amount of heat supplied to the engine, and  $Q_L$  is the amount of heat rejected by the engine.

Refrigerators and heat pumps are devices that absorb heat from low-temperature media and reject it to higher-temperature ones. The performance of a refrigerator or a heat pump is expressed in terms of the *coefficient of performance*, which is defined as

$$\text{COP}_R = \frac{Q_L}{W_{\text{net,in}}} = \frac{1}{Q_H/Q_L - 1}$$

$$\text{COP}_{\text{HP}} = \frac{Q_H}{W_{\text{net,in}}} = \frac{1}{1 - Q_L/Q_H}$$

The *Kelvin–Planck statement* of the second law of thermodynamics states that no heat engine can produce a net amount of work while exchanging heat with a single reservoir only. The *Clausius statement* of the second law states that no device can transfer heat from a cooler body to a warmer one without leaving an effect on the surroundings.

Any device that violates the first or the second law of thermodynamics is called a *perpetual-motion machine*.

A process is said to be *reversible* if both the system and the surroundings can be restored to their original conditions. Any other process is *irreversible*. The effects such as friction, non-quasi-equilibrium expansion or compression, and heat transfer through a finite temperature difference render a process irreversible and are called *irreversibilities*.

The *Carnot cycle* is a reversible cycle that is composed of four reversible processes, two isothermal and two adiabatic. The *Carnot principles* state that the thermal efficiencies of all reversible heat engines operating between the same two reservoirs are the same, and that no heat engine is more efficient

than a reversible one operating between the same two reservoirs. These statements form the basis for establishing a *thermodynamic temperature scale* related to the heat transfers between a reversible device and the high- and low-temperature reservoirs by

$$\left(\frac{Q_H}{Q_L}\right)_{\text{rev}} = \frac{T_H}{T_L}$$

Therefore, the  $Q_H/Q_L$  ratio can be replaced by  $T_H/T_L$  for reversible devices, where  $T_H$  and  $T_L$  are the absolute temperatures of the high- and low-temperature reservoirs, respectively.

A heat engine that operates on the reversible Carnot cycle is called a *Carnot heat engine*. The thermal efficiency of a Carnot heat engine, as well as all other reversible heat engines, is given by

$$\eta_{\text{th,rev}} = 1 - \frac{T_L}{T_H}$$

This is the maximum efficiency a heat engine operating between two reservoirs at temperatures  $T_H$  and  $T_L$  can have.

The COPs of reversible refrigerators and heat pumps are given in a similar manner as

$$\text{COP}_{R,\text{rev}} = \frac{1}{T_H/T_L - 1}$$

and

$$\text{COP}_{\text{HP,rev}} = \frac{1}{1 - T_L/T_H}$$

Again, these are the highest COPs a refrigerator or a heat pump operating between the temperature limits of  $T_H$  and  $T_L$  can have.

## REFERENCES AND SUGGESTED READINGS

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2. W. Z. Black and J. G. Hartley. *Thermodynamics*. New York: Harper & Row, 1985.
3. D. Stewart. “Wheels Go Round and Round, but Always Run Down.” November 1986, *Smithsonian*, pp. 193–208.
4. K. Wark and D. E. Richards. *Thermodynamics*. 6th ed. New York: McGraw-Hill, 1999.

## PROBLEMS\*

### Second Law of Thermodynamics and Thermal Energy Reservoirs

**6–1C** A mechanic claims to have developed a car engine that runs on water instead of gasoline. What is your response to this claim?

**6–2C** Describe an imaginary process that satisfies the first law but violates the second law of thermodynamics.

\* Problems designated by a “C” are concept questions, and students are encouraged to answer them all. Problems designated by an “E” are in English units, and the SI users can ignore them. Problems with a CD-EES icon  are solved using EES, and complete solutions together with parametric studies are included on the enclosed DVD. Problems with a computer-EES icon  are comprehensive in nature, and are intended to be solved with a computer, preferably using the EES software that accompanies this text.

**6-3C** Describe an imaginary process that satisfies the second law but violates the first law of thermodynamics.

**6-4C** Describe an imaginary process that violates both the first and the second laws of thermodynamics.

**6-5C** An experimentalist claims to have raised the temperature of a small amount of water to 150°C by transferring heat from high-pressure steam at 120°C. Is this a reasonable claim? Why? Assume no refrigerator or heat pump is used in the process.

**6-6C** What is a thermal energy reservoir? Give some examples.

**6-7C** Consider the process of baking potatoes in a conventional oven. Can the hot air in the oven be treated as a thermal energy reservoir? Explain.

**6-8C** Consider the energy generated by a TV set. What is a suitable choice for a thermal energy reservoir?

### Heat Engines and Thermal Efficiency

**6-9C** Is it possible for a heat engine to operate without rejecting any waste heat to a low-temperature reservoir? Explain.

**6-10C** What are the characteristics of all heat engines?

**6-11C** Consider a pan of water being heated (a) by placing it on an electric range and (b) by placing a heating element in the water. Which method is a more efficient way of heating water? Explain.

**6-12C** Baseboard heaters are basically electric resistance heaters and are frequently used in space heating. A home owner claims that her 5-year-old baseboard heaters have a conversion efficiency of 100 percent. Is this claim in violation of any thermodynamic laws? Explain.

**6-13C** What is the Kelvin–Planck expression of the second law of thermodynamics?

**6-14C** Does a heat engine that has a thermal efficiency of 100 percent necessarily violate (a) the first law and (b) the second law of thermodynamics? Explain.

**6-15C** In the absence of any friction and other irreversibilities, can a heat engine have an efficiency of 100 percent? Explain.

**6-16C** Are the efficiencies of all the work-producing devices, including the hydroelectric power plants, limited by the Kelvin–Planck statement of the second law? Explain.

**6-17** A 600-MW steam power plant, which is cooled by a nearby river, has a thermal efficiency of 40 percent. Determine the rate of heat transfer to the river water. Will the actual heat transfer rate be higher or lower than this value? Why?

**6-18** A steam power plant receives heat from a furnace at a rate of 280 GJ/h. Heat losses to the surrounding air from the steam as it passes through the pipes and other components are estimated to be about 8 GJ/h. If the waste heat is trans-

ferred to the cooling water at a rate of 145 GJ/h, determine (a) net power output and (b) the thermal efficiency of this power plant. *Answers: (a) 35.3 MW, (b) 45.4 percent*

**6-19E** A car engine with a power output of 110 hp has a thermal efficiency of 28 percent. Determine the rate of fuel consumption if the heating value of the fuel is 19,000 Btu/lbm.

**6-20** A steam power plant with a power output of 150 MW consumes coal at a rate of 60 tons/h. If the heating value of the coal is 30,000 kJ/kg, determine the overall efficiency of this plant. *Answer: 30.0 percent*

**6-21** An automobile engine consumes fuel at a rate of 28 L/h and delivers 60 kW of power to the wheels. If the fuel has a heating value of 44,000 kJ/kg and a density of 0.8 g/cm<sup>3</sup>, determine the efficiency of this engine. *Answer: 21.9 percent*

**6-22E** Solar energy stored in large bodies of water, called solar ponds, is being used to generate electricity. If such a solar power plant has an efficiency of 4 percent and a net power output of 350 kW, determine the average value of the required solar energy collection rate, in Btu/h.

**6-23** In 2001, the United States produced 51 percent of its electricity in the amount of  $1.878 \times 10^{12}$  kWh from coal-fired power plants. Taking the average thermal efficiency to be 34 percent, determine the amount of thermal energy rejected by the coal-fired power plants in the United States that year.

**6-24** The Department of Energy projects that between the years 1995 and 2010, the United States will need to build new power plants to generate an additional 150,000 MW of electricity to meet the increasing demand for electric power. One possibility is to build coal-fired power plants, which cost \$1300 per kW to construct and have an efficiency of 34 percent. Another possibility is to use the clean-burning Integrated Gasification Combined Cycle (IGCC) plants where the coal is subjected to heat and pressure to gasify it while removing sulfur and particulate matter from it. The gaseous coal is then burned in a gas turbine, and part of the waste heat from the exhaust gases is recovered to generate steam for the steam turbine. Currently the construction of IGCC plants costs about \$1500 per kW, but their efficiency is about 45 percent. The average heating value of the coal is about 28,000,000 kJ per ton (that is, 28,000,000 kJ of heat is released when 1 ton of coal is burned). If the IGCC plant is to recover its cost difference from fuel savings in five years, determine what the price of coal should be in \$ per ton.

**6-25**  Reconsider Prob. 6-24. Using EES (or other) software, investigate the price of coal for varying simple payback periods, plant construction costs, and operating efficiency.

**6-26** Repeat Prob. 6-24 for a simple payback period of three years instead of five years.

**6-27E** An Ocean Thermal Energy Conversion (OTEC) power plant built in Hawaii in 1987 was designed to operate

between the temperature limits of 86°F at the ocean surface and 41°F at a depth of 2100 ft. About 13,300 gpm of cold seawater was to be pumped from deep ocean through a 40-in-diameter pipe to serve as the cooling medium or heat sink. If the cooling water experiences a temperature rise of 6°F and the thermal efficiency is 2.5 percent, determine the amount of power generated. Take the density of seawater to be 64 lbm/ft<sup>3</sup>.

**6-28** A coal-burning steam power plant produces a net power of 300 MW with an overall thermal efficiency of 32 percent. The actual gravimetric air–fuel ratio in the furnace is calculated to be 12 kg air/kg fuel. The heating value of the coal is 28,000 kJ/kg. Determine (a) the amount of coal consumed during a 24-hour period and (b) the rate of air flowing through the furnace. *Answers: (a)  $2.89 \times 10^6$  kg, (b) 402 kg/s*

### Refrigerators and Heat Pumps

**6-29C** What is the difference between a refrigerator and a heat pump?

**6-30C** What is the difference between a refrigerator and an air conditioner?

**6-31C** In a refrigerator, heat is transferred from a lower-temperature medium (the refrigerated space) to a higher-temperature one (the kitchen air). Is this a violation of the second law of thermodynamics? Explain.

**6-32C** A heat pump is a device that absorbs energy from the cold outdoor air and transfers it to the warmer indoors. Is this a violation of the second law of thermodynamics? Explain.

**6-33C** Define the coefficient of performance of a refrigerator in words. Can it be greater than unity?

**6-34C** Define the coefficient of performance of a heat pump in words. Can it be greater than unity?

**6-35C** A heat pump that is used to heat a house has a COP of 2.5. That is, the heat pump delivers 2.5 kWh of energy to the house for each 1 kWh of electricity it consumes. Is this a violation of the first law of thermodynamics? Explain.

**6-36C** A refrigerator has a COP of 1.5. That is, the refrigerator removes 1.5 kWh of energy from the refrigerated space for each 1 kWh of electricity it consumes. Is this a violation of the first law of thermodynamics? Explain.

**6-37C** What is the Clausius expression of the second law of thermodynamics?

**6-38C** Show that the Kelvin–Planck and the Clausius expressions of the second law are equivalent.

**6-39** A household refrigerator with a COP of 1.2 removes heat from the refrigerated space at a rate of 60 kJ/min. Determine (a) the electric power consumed by the refrigerator and (b) the rate of heat transfer to the kitchen air. *Answers: (a) 0.83 kW, (b) 110 kJ/min*

**6-40** An air conditioner removes heat steadily from a house at a rate of 750 kJ/min while drawing electric power at a rate of 6 kW. Determine (a) the COP of this air conditioner and (b) the rate of heat transfer to the outside air. *Answers: (a) 2.08, (b) 1110 kJ/min*

**6-41** A household refrigerator runs one-fourth of the time and removes heat from the food compartment at an average rate of 800 kJ/h. If the COP of the refrigerator is 2.2, determine the power the refrigerator draws when running.

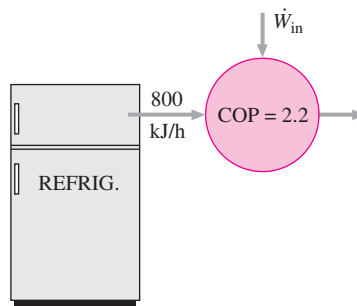


FIGURE P6-41

**6-42E** Water enters an ice machine at 55°F and leaves as ice at 25°F. If the COP of the ice machine is 2.4 during this operation, determine the required power input for an ice production rate of 28 lbm/h. (169 Btu of energy needs to be removed from each lbm of water at 55°F to turn it into ice at 25°F.)

**6-43** A household refrigerator that has a power input of 450 W and a COP of 2.5 is to cool five large watermelons, 10 kg each, to 8°C. If the watermelons are initially at 20°C, determine how long it will take for the refrigerator to cool them. The watermelons can be treated as water whose specific heat is 4.2 kJ/kg · °C. Is your answer realistic or optimistic? Explain. *Answer: 2240 s*

**6-44** When a man returns to his well-sealed house on a summer day, he finds that the house is at 32°C. He turns on the air conditioner, which cools the entire house to 20°C in 15 min. If the COP of the air-conditioning system is 2.5, determine the power drawn by the air conditioner. Assume the entire mass within the house is equivalent to 800 kg of air for which  $c_v = 0.72$  kJ/kg · °C and  $c_p = 1.0$  kJ/kg · °C.

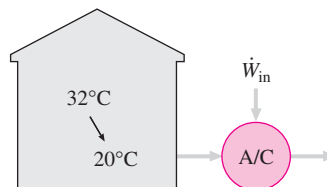


FIGURE P6-44

**6-45**  Reconsider Prob. 6-44. Using EES (or other) software, determine the power input required by the air conditioner to cool the house as a function for air-conditioner EER ratings in the range 9 to 16. Discuss your results and include representative costs of air-conditioning units in the EER rating range.

**6-46** Determine the COP of a refrigerator that removes heat from the food compartment at a rate of 5040 kJ/h for each kW of power it consumes. Also, determine the rate of heat rejection to the outside air.

**6-47** Determine the COP of a heat pump that supplies energy to a house at a rate of 8000 kJ/h for each kW of electric power it draws. Also, determine the rate of energy absorption from the outdoor air. *Answers: 2.22, 4400 kJ/h*

**6-48** A house that was heated by electric resistance heaters consumed 1200 kWh of electric energy in a winter month. If this house were heated instead by a heat pump that has an average COP of 2.4, determine how much money the home owner would have saved that month. Assume a price of 8.5¢/kWh for electricity.

**6-49E** A heat pump with a COP of 2.5 supplies energy to a house at a rate of 60,000 Btu/h. Determine (a) the electric power drawn by the heat pump and (b) the rate of heat absorption from the outside air. *Answers: (a) 9.43 hp, (b) 36,000 Btu/h*

**6-50** A heat pump used to heat a house runs about one-third of the time. The house is losing heat at an average rate of 22,000 kJ/h. If the COP of the heat pump is 2.8, determine the power the heat pump draws when running.

**6-51** A heat pump is used to maintain a house at a constant temperature of 23°C. The house is losing heat to the outside air through the walls and the windows at a rate of 60,000 kJ/h while the energy generated within the house from people, lights, and appliances amounts to 4000 kJ/h. For a COP of 2.5, determine the required power input to the heat pump.

*Answer: 6.22 kW*

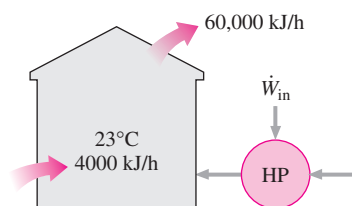


FIGURE P6-51

**6-52E** Consider an office room that is being cooled adequately by a 12,000 Btu/h window air conditioner. Now it is decided to convert this room into a computer room by installing several computers, terminals, and printers with a total rated power of 3.5 kW. The facility has several 4000 Btu/h air conditioners in storage that can be installed to

meet the additional cooling requirements. Assuming a usage factor of 0.4 (i.e., only 40 percent of the rated power will be consumed at any given time) and additional occupancy of four people, each generating heat at a rate of 100 W, determine how many of these air conditioners need to be installed to the room.

**6-53** Consider a building whose annual air-conditioning load is estimated to be 120,000 kWh in an area where the unit cost of electricity is \$0.10/kWh. Two air conditioners are considered for the building. Air conditioner A has a seasonal average COP of 3.2 and costs \$5500 to purchase and install. Air conditioner B has a seasonal average COP of 5.0 and costs \$7000 to purchase and install. All else being equal, determine which air conditioner is a better buy.

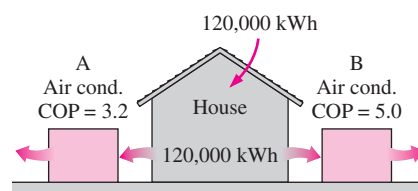


FIGURE P6-53

**6-54** Refrigerant-134a enters the condenser of a residential heat pump at 800 kPa and 35°C at a rate of 0.018 kg/s and leaves at 800 kPa as a saturated liquid. If the compressor consumes 1.2 kW of power, determine (a) the COP of the heat pump and (b) the rate of heat absorption from the outside air.

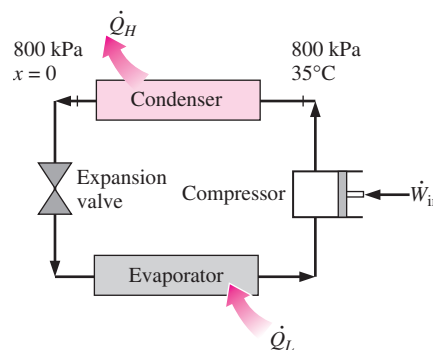


FIGURE P6-54

**6-55** Refrigerant-134a enters the evaporator coils placed at the back of the freezer section of a household refrigerator at 120 kPa with a quality of 20 percent and leaves at 120 kPa and  $-20^{\circ}\text{C}$ . If the compressor consumes 450 W of power and the COP the refrigerator is 1.2, determine (a) the mass flow rate of the refrigerant and (b) the rate of heat rejected to the kitchen air. *Answers: (a) 0.00311 kg/s, (b) 990 W*

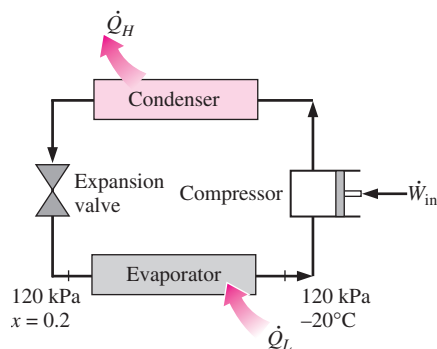


FIGURE P6-55

### Perpetual-Motion Machines

**6-56C** An inventor claims to have developed a resistance heater that supplies 1.2 kWh of energy to a room for each kWh of electricity it consumes. Is this a reasonable claim, or has the inventor developed a perpetual-motion machine? Explain.

**6-57C** It is common knowledge that the temperature of air rises as it is compressed. An inventor thought about using this high-temperature air to heat buildings. He used a compressor driven by an electric motor. The inventor claims that the compressed hot-air system is 25 percent more efficient than a resistance heating system that provides an equivalent amount of heating. Is this claim valid, or is this just another perpetual-motion machine? Explain.

### Reversible and Irreversible Processes

**6-58C** A cold canned drink is left in a warmer room where its temperature rises as a result of heat transfer. Is this a reversible process? Explain.

**6-59C** Why are engineers interested in reversible processes even though they can never be achieved?

**6-60C** Why does a nonquasi-equilibrium compression process require a larger work input than the corresponding quasi-equilibrium one?

**6-61C** Why does a nonquasi-equilibrium expansion process deliver less work than the corresponding quasi-equilibrium one?

**6-62C** How do you distinguish between internal and external irreversibilities?

**6-63C** Is a reversible expansion or compression process necessarily quasi-equilibrium? Is a quasi-equilibrium expansion or compression process necessarily reversible? Explain.

### The Carnot Cycle and Carnot Principles

**6-64C** What are the four processes that make up the Carnot cycle?

**6-65C** What are the two statements known as the Carnot principles?

**6-66C** Somebody claims to have developed a new reversible heat-engine cycle that has a higher theoretical efficiency than the Carnot cycle operating between the same temperature limits. How do you evaluate this claim?

**6-67C** Somebody claims to have developed a new reversible heat-engine cycle that has the same theoretical efficiency as the Carnot cycle operating between the same temperature limits. Is this a reasonable claim?

**6-68C** Is it possible to develop (a) an actual and (b) a reversible heat-engine cycle that is more efficient than a Carnot cycle operating between the same temperature limits? Explain.

### Carnot Heat Engines

**6-69C** Is there any way to increase the efficiency of a Carnot heat engine other than by increasing  $T_H$  or decreasing  $T_L$ ?

**6-70C** Consider two actual power plants operating with solar energy. Energy is supplied to one plant from a solar pond at 80°C and to the other from concentrating collectors that raise the water temperature to 600°C. Which of these power plants will have a higher efficiency? Explain.

**6-71** A Carnot heat engine operates between a source at 1000 K and a sink at 300 K. If the heat engine is supplied with heat at a rate of 800 kJ/min, determine (a) the thermal efficiency and (b) the power output of this heat engine.

*Answers: (a) 70 percent, (b) 9.33 kW*

**6-72** A Carnot heat engine receives 650 kJ of heat from a source of unknown temperature and rejects 250 kJ of it to a sink at 24°C. Determine (a) the temperature of the source and (b) the thermal efficiency of the heat engine.

**6-73**  A heat engine operates between a source at 550°C and a sink at 25°C. If heat is supplied to the heat engine at a steady rate of 1200 kJ/min, determine the maximum power output of this heat engine.

**6-74**  Reconsider Prob. 6-73. Using EES (or other) software, study the effects of the temperatures of the heat source and the heat sink on the power produced and the cycle thermal efficiency. Let the source temperature vary from 300 to 1000°C, and the sink temperature to vary from 0 to 50°C. Plot the power produced and the cycle efficiency against the source temperature for sink temperatures of 0°C, 25°C, and 50°C, and discuss the results.

**6-75E** A heat engine is operating on a Carnot cycle and has a thermal efficiency of 55 percent. The waste heat from this engine is rejected to a nearby lake at 60°F at a rate of 800 Btu/min. Determine (a) the power output of the engine and (b) the temperature of the source. *Answers: (a) 23.1 hp, (b) 1156 R*

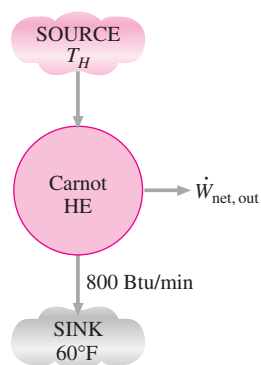


FIGURE P6-75E

**6-76** In tropical climates, the water near the surface of the ocean remains warm throughout the year as a result of solar energy absorption. In the deeper parts of the ocean, however, the water remains at a relatively low temperature since the sun's rays cannot penetrate very far. It is proposed to take advantage of this temperature difference and construct a power plant that will absorb heat from the warm water near the surface and reject the waste heat to the cold water a few hundred meters below. Determine the maximum thermal efficiency of such a plant if the water temperatures at the two respective locations are 24 and 3°C.

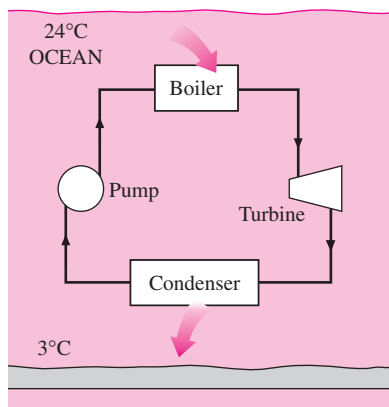


FIGURE P6-76

**6-77** An innovative way of power generation involves the utilization of geothermal energy—the energy of hot water that exists naturally underground—as the heat source. If a supply of hot water at 140°C is discovered at a location where the environmental temperature is 20°C, determine the maximum thermal efficiency a geothermal power plant built at that location can have. **Answer: 29.1 percent**

**6-78** An inventor claims to have developed a heat engine that receives 700 kJ of heat from a source at 500 K and produces 300 kJ of net work while rejecting the waste heat to a sink at 290 K. Is this a reasonable claim? Why?

**6-79E** An experimentalist claims that, based on his measurements, a heat engine receives 300 Btu of heat from a source of 900 R, converts 160 Btu of it to work, and rejects the rest as waste heat to a sink at 540 R. Are these measurements reasonable? Why?

**6-80** A geothermal power plant uses geothermal water extracted at 160°C at a rate of 440 kg/s as the heat source and produces 22 MW of net power. If the environment temperature is 25°C, determine (a) the actual thermal efficiency, (b) the maximum possible thermal efficiency, and (c) the actual rate of heat rejection from this power plant.

### Carnot Refrigerators and Heat Pumps

**6-81C** How can we increase the COP of a Carnot refrigerator?

**6-82C** What is the highest COP that a refrigerator operating between temperature levels  $T_L$  and  $T_H$  can have?

**6-83C** In an effort to conserve energy in a heat-engine cycle, somebody suggests incorporating a refrigerator that will absorb some of the waste energy  $Q_L$  and transfer it to the energy source of the heat engine. Is this a smart idea? Explain.

**6-84C** It is well established that the thermal efficiency of a heat engine increases as the temperature  $T_L$  at which heat is rejected from the heat engine decreases. In an effort to increase the efficiency of a power plant, somebody suggests refrigerating the cooling water before it enters the condenser, where heat rejection takes place. Would you be in favor of this idea? Why?

**6-85C** It is well known that the thermal efficiency of heat engines increases as the temperature of the energy source increases. In an attempt to improve the efficiency of a power plant, somebody suggests transferring heat from the available energy source to a higher-temperature medium by a heat pump before energy is supplied to the power plant. What do you think of this suggestion? Explain.

**6-86** A Carnot refrigerator operates in a room in which the temperature is 22°C and consumes 2 kW of power when operating. If the food compartment of the refrigerator is to be maintained at 3°C, determine the rate of heat removal from the food compartment.

**6-87** A refrigerator is to remove heat from the cooled space at a rate of 300 kJ/min to maintain its temperature at  $-8^{\circ}\text{C}$ .

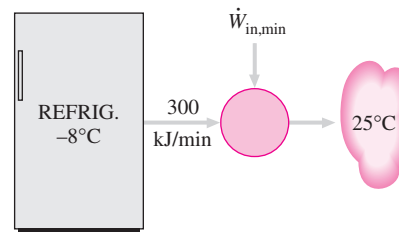


FIGURE P6-87

If the air surrounding the refrigerator is at  $25^{\circ}\text{C}$ , determine the minimum power input required for this refrigerator.

*Answer: 0.623 kW*

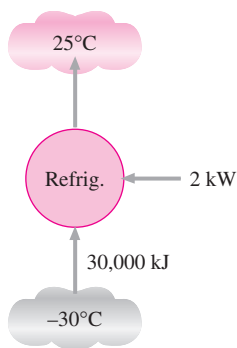
**6-88** An air-conditioning system operating on the reversed Carnot cycle is required to transfer heat from a house at a rate of  $750\text{ kJ/min}$  to maintain its temperature at  $24^{\circ}\text{C}$ . If the outdoor air temperature is  $35^{\circ}\text{C}$ , determine the power required to operate this air-conditioning system. *Answer: 0.46 kW*

**6-89E** An air-conditioning system is used to maintain a house at  $72^{\circ}\text{F}$  when the temperature outside is  $90^{\circ}\text{F}$ . If this air-conditioning system draws  $5\text{ hp}$  of power when operating, determine the maximum rate of heat removal from the house that it can accomplish.

**6-90** A Carnot refrigerator operates in a room in which the temperature is  $25^{\circ}\text{C}$ . The refrigerator consumes  $500\text{ W}$  of power when operating and has a COP of  $4.5$ . Determine (a) the rate of heat removal from the refrigerated space and (b) the temperature of the refrigerated space. *Answers: (a)  $135\text{ kJ/min}$ , (b)  $-29.2^{\circ}\text{C}$*

**6-91** An inventor claims to have developed a refrigeration system that removes heat from the closed region at  $-12^{\circ}\text{C}$  and transfers it to the surrounding air at  $25^{\circ}\text{C}$  while maintaining a COP of  $6.5$ . Is this claim reasonable? Why?

**6-92** During an experiment conducted in a room at  $25^{\circ}\text{C}$ , a laboratory assistant measures that a refrigerator that draws  $2\text{ kW}$  of power has removed  $30,000\text{ kJ}$  of heat from the refrigerated space, which is maintained at  $-30^{\circ}\text{C}$ . The running time of the refrigerator during the experiment was  $20\text{ min}$ . Determine if these measurements are reasonable.

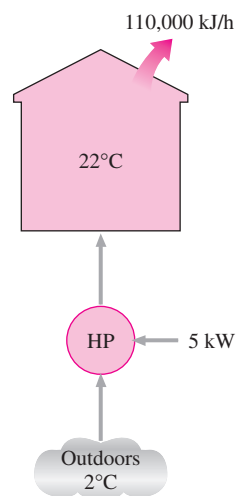


**FIGURE P6-92**

**6-93E** An air-conditioning system is used to maintain a house at  $75^{\circ}\text{F}$  when the temperature outside is  $95^{\circ}\text{F}$ . The house is gaining heat through the walls and the windows at a rate of  $800\text{ Btu/min}$ , and the heat generation rate within the house from people, lights, and appliances amounts to  $100\text{ Btu/min}$ . Determine the minimum power input required for this air-conditioning system. *Answer: 0.79 hp*

**6-94** A heat pump is used to heat a house and maintain it at  $24^{\circ}\text{C}$ . On a winter day when the outdoor air temperature is  $-5^{\circ}\text{C}$ , the house is estimated to lose heat at a rate of  $80,000\text{ kJ/h}$ . Determine the minimum power required to operate this heat pump.

**6-95** A heat pump is used to maintain a house at  $22^{\circ}\text{C}$  by extracting heat from the outside air on a day when the outside air temperature is  $2^{\circ}\text{C}$ . The house is estimated to lose heat at a rate of  $110,000\text{ kJ/h}$ , and the heat pump consumes  $5\text{ kW}$  of electric power when running. Is this heat pump powerful enough to do the job?



**FIGURE P6-95**

**6-96** The structure of a house is such that it loses heat at a rate of  $5400\text{ kJ/h}$  per  $^{\circ}\text{C}$  difference between the indoors and outdoors. A heat pump that requires a power input of  $6\text{ kW}$  is used to maintain this house at  $21^{\circ}\text{C}$ . Determine the lowest outdoor temperature for which the heat pump can meet the heating requirements of this house. *Answer:  $-13.3^{\circ}\text{C}$*

**6-97** The performance of a heat pump degrades (i.e., its COP decreases) as the temperature of the heat source decreases. This makes using heat pumps at locations with severe weather conditions unattractive. Consider a house that is heated and maintained at  $20^{\circ}\text{C}$  by a heat pump during the winter. What is the maximum COP for this heat pump if heat is extracted from the outdoor air at (a)  $10^{\circ}\text{C}$ , (b)  $-5^{\circ}\text{C}$ , and (c)  $-30^{\circ}\text{C}$ ?

**6-98E** A heat pump is to be used for heating a house in winter. The house is to be maintained at  $78^{\circ}\text{F}$  at all times. When the temperature outdoors drops to  $25^{\circ}\text{F}$ , the heat losses from the house are estimated to be  $55,000\text{ Btu/h}$ . Determine the minimum power required to run this heat pump if heat is extracted from (a) the outdoor air at  $25^{\circ}\text{F}$  and (b) the well water at  $50^{\circ}\text{F}$ .

**6-99** A Carnot heat pump is to be used to heat a house and maintain it at  $20^{\circ}\text{C}$  in winter. On a day when the average outdoor temperature remains at about  $2^{\circ}\text{C}$ , the house is estimated to lose heat at a rate of  $82,000\text{ kJ/h}$ . If the heat pump consumes  $8\text{ kW}$  of power while operating, determine (a) how long the heat pump ran on that day; (b) the total heating costs, assuming an average price of  $8.5\text{¢/kWh}$  for electricity; and (c) the heating cost for the same day if resistance heating is used instead of a heat pump. *Answers: (a) 4.19 h, (b) \\$2.85, (c) \\$46.47*

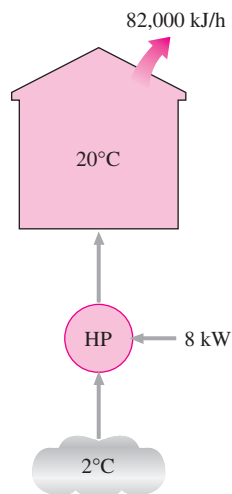


FIGURE P6-99

**6-100** A Carnot heat engine receives heat from a reservoir at  $900^{\circ}\text{C}$  at a rate of  $800\text{ kJ/min}$  and rejects the waste heat to the ambient air at  $27^{\circ}\text{C}$ . The entire work output of the heat engine is used to drive a refrigerator that removes heat from the refrigerated space at  $-5^{\circ}\text{C}$  and transfers it to the same ambient air at  $27^{\circ}\text{C}$ . Determine (a) the maximum rate of heat removal from the refrigerated space and (b) the total rate of heat rejection to the ambient air. *Answers: (a)  $4982\text{ kJ/min}$ , (b)  $5782\text{ kJ}$*

**6-101E** A Carnot heat engine receives heat from a reservoir at  $1700^{\circ}\text{F}$  at a rate of  $700\text{ Btu/min}$  and rejects the waste heat to the ambient air at  $80^{\circ}\text{F}$ . The entire work output of the heat engine is used to drive a refrigerator that removes heat from the refrigerated space at  $20^{\circ}\text{F}$  and transfers it to the same ambient air at  $80^{\circ}\text{F}$ . Determine (a) the maximum rate of heat removal from the refrigerated space and (b) the total rate of heat rejection to the ambient air. *Answers: (a)  $4200\text{ Btu/min}$ , (b)  $4900\text{ Btu/min}$*

**6-102** A commercial refrigerator with refrigerant-134a as the working fluid is used to keep the refrigerated space at  $-35^{\circ}\text{C}$  by rejecting waste heat to cooling water that enters the condenser at  $18^{\circ}\text{C}$  at a rate of  $0.25\text{ kg/s}$  and leaves at

$26^{\circ}\text{C}$ . The refrigerant enters the condenser at  $1.2\text{ MPa}$  and  $50^{\circ}\text{C}$  and leaves at the same pressure subcooled by  $5^{\circ}\text{C}$ . If the compressor consumes  $3.3\text{ kW}$  of power, determine (a) the mass flow rate of the refrigerant, (b) the refrigeration load, (c) the COP, and (d) the minimum power input to the compressor for the same refrigeration load.

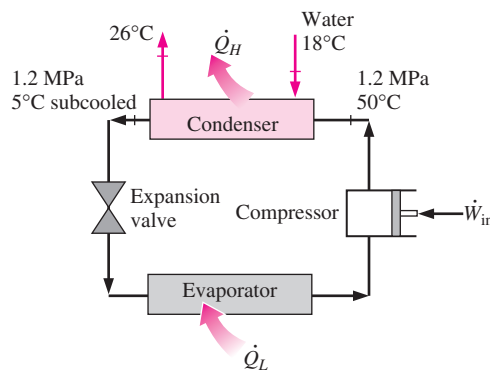


FIGURE P6-102

**6-103** An air-conditioner with refrigerant-134a as the working fluid is used to keep a room at  $26^{\circ}\text{C}$  by rejecting the waste heat to the outdoor air at  $34^{\circ}\text{C}$ . The room gains heat through the walls and the windows at a rate of  $250\text{ kJ/min}$  while the heat generated by the computer, TV, and lights amounts to  $900\text{ W}$ . The refrigerant enters the compressor at  $500\text{ kPa}$  as a saturated vapor at a rate of  $100\text{ L/min}$  and leaves at  $1200\text{ kPa}$  and  $50^{\circ}\text{C}$ . Determine (a) the actual COP, (b) the maximum COP, and (c) the minimum volume flow rate of the refrigerant at the compressor inlet for the same compressor inlet and exit conditions. *Answers: (a) 6.59, (b) 37.4, (c)  $17.6\text{ L/min}$*

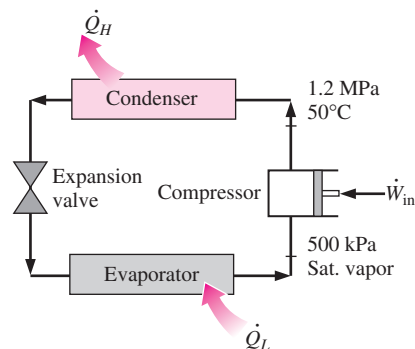


FIGURE P6-103

**Special Topic: Household Refrigerators**

**6-104C** Someone proposes that the refrigeration system of a supermarket be oversized so that the entire air-conditioning needs of the store can be met by refrigerated air without installing any air-conditioning system. What do you think of this proposal?

**6-105C** Someone proposes that the entire refrigerator/freezer requirements of a store be met using a large freezer that supplies sufficient cold air at  $-20^{\circ}\text{C}$  instead of installing separate refrigerators and freezers. What do you think of this proposal?

**6-106C** Explain how you can reduce the energy consumption of your household refrigerator.

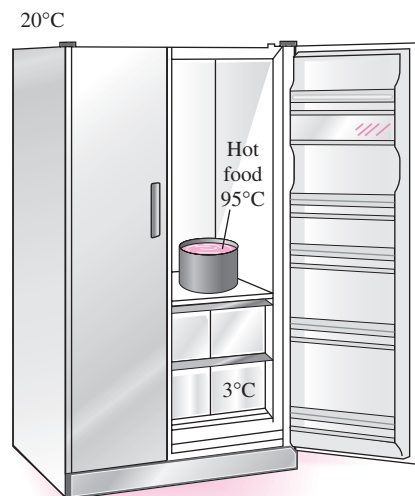
**6-107C** Why is it important to clean the condenser coils of a household refrigerator a few times a year? Also, why is it important not to block airflow through the condenser coils?

**6-108C** Why are today's refrigerators much more efficient than those built in the past?

**6-109** The "Energy Guide" label of a refrigerator states that the refrigerator will consume \$74 worth of electricity per year under normal use if the cost of electricity is \$0.07/kWh. If the electricity consumed by the lightbulb is negligible and the refrigerator consumes 300 W when running, determine the fraction of the time the refrigerator will run.

**6-110** The interior lighting of refrigerators is usually provided by incandescent lamps whose switches are actuated by the opening of the refrigerator door. Consider a refrigerator whose 40-W lightbulb remains on about 60 h per year. It is proposed to replace the lightbulb by an energy-efficient bulb that consumes only 18 W but costs \$25 to purchase and install. If the refrigerator has a coefficient of performance of 1.3 and the cost of electricity is 8 cents per kWh, determine if the energy savings of the proposed lightbulb justify its cost.

**6-111** It is commonly recommended that hot foods be cooled first to room temperature by simply waiting a while before they are put into the refrigerator to save energy. Despite this commonsense recommendation, a person keeps cooking a large pan of stew twice a week and putting the pan into the refrigerator while it is still hot, thinking that the money saved is probably too little. But he says he can be convinced if you can show that the money saved is significant. The average mass of the pan and its contents is 5 kg. The average temperature of the kitchen is  $20^{\circ}\text{C}$ , and the average temperature of the food is  $95^{\circ}\text{C}$  when it is taken off the stove. The refrigerated space is maintained at  $3^{\circ}\text{C}$ , and the average specific heat of the food and the pan can be taken to be  $3.9 \text{ kJ/kg} \cdot ^{\circ}\text{C}$ . If the refrigerator has a coefficient of performance of 1.2 and the cost of electricity is 10 cents per kWh, determine how much this person will save a year by waiting for the food to cool to room temperature before putting it into the refrigerator.

**FIGURE P6-111**

**6-112** It is often stated that the refrigerator door should be opened as few times as possible for the shortest duration of time to save energy. Consider a household refrigerator whose interior volume is  $0.9 \text{ m}^3$  and average internal temperature is  $4^{\circ}\text{C}$ . At any given time, one-third of the refrigerated space is occupied by food items, and the remaining  $0.6 \text{ m}^3$  is filled with air. The average temperature and pressure in the kitchen are  $20^{\circ}\text{C}$  and  $95 \text{ kPa}$ , respectively. Also, the moisture contents of the air in the kitchen and the refrigerator are 0.010 and 0.004 kg per kg of air, respectively, and thus 0.006 kg of water vapor is condensed and removed for each kg of air that enters. The refrigerator door is opened an average of 8 times a day, and each time half of the air volume in the refrigerator is replaced by the warmer kitchen air. If the refrigerator has a coefficient of performance of 1.4 and the cost of electricity is 7.5 cents per kWh, determine the cost of the energy wasted per year as a result of opening the refrigerator door. What would your answer be if the kitchen air were very dry and thus a negligible amount of water vapor condensed in the refrigerator?

**Review Problems**

**6-113** Consider a Carnot heat-engine cycle executed in a steady-flow system using steam as the working fluid. The cycle has a thermal efficiency of 30 percent, and steam changes from saturated liquid to saturated vapor at  $275^{\circ}\text{C}$  during the heat addition process. If the mass flow rate of the steam is  $3 \text{ kg/s}$ , determine the net power output of this engine, in kW.

**6-114** A heat pump with a COP of 2.4 is used to heat a house. When running, the heat pump consumes 8 kW of electric power. If the house is losing heat to the outside at an average rate of  $40,000 \text{ kJ/h}$  and the temperature of the house is  $3^{\circ}\text{C}$  when the heat pump is turned on, determine how long

it will take for the temperature in the house to rise to 22°C. Assume the house is well sealed (i.e., no air leaks) and take the entire mass within the house (air, furniture, etc.) to be equivalent to 2000 kg of air.

**6-115** An old gas turbine has an efficiency of 21 percent and develops a power output of 6000 kW. Determine the fuel consumption rate of this gas turbine, in L/min, if the fuel has a heating value of 42,000 kJ/kg and a density of 0.8 g/cm<sup>3</sup>.

**6-116** Show that  $\text{COP}_{\text{HP}} = \text{COP}_{\text{R}} + 1$  when both the heat pump and the refrigerator have the same  $Q_L$  and  $Q_H$  values.

**6-117** An air-conditioning system is used to maintain a house at a constant temperature of 20°C. The house is gaining heat from outdoors at a rate of 20,000 kJ/h, and the heat generated in the house from the people, lights, and appliances amounts to 8000 kJ/h. For a COP of 2.5, determine the required power input to this air-conditioning system.

*Answer: 3.11 kW*

**6-118** Consider a Carnot heat-engine cycle executed in a closed system using 0.01 kg of refrigerant-134a as the working fluid. The cycle has a thermal efficiency of 15 percent, and the refrigerant-134a changes from saturated liquid to saturated vapor at 50°C during the heat addition process. Determine the net work output of this engine per cycle.

**6-119** A heat pump with a COP of 2.8 is used to heat an air-tight house. When running, the heat pump consumes 5 kW of power. If the temperature in the house is 7°C when the heat pump is turned on, how long will it take for the heat pump to raise the temperature of the house to 22°C? Is this answer realistic or optimistic? Explain. Assume the entire mass within the house (air, furniture, etc.) is equivalent to 1500 kg of air. *Answer: 19.2 min*

**6-120** A promising method of power generation involves collecting and storing solar energy in large artificial lakes a few meters deep, called solar ponds. Solar energy is absorbed by all parts of the pond, and the water temperature rises everywhere. The top part of the pond, however, loses to the

atmosphere much of the heat it absorbs, and as a result, its temperature drops. This cool water serves as insulation for the bottom part of the pond and helps trap the energy there. Usually, salt is planted at the bottom of the pond to prevent the rise of this hot water to the top. A power plant that uses an organic fluid, such as alcohol, as the working fluid can be operated between the top and the bottom portions of the pond. If the water temperature is 35°C near the surface and 80°C near the bottom of the pond, determine the maximum thermal efficiency that this power plant can have. Is it realistic to use 35 and 80°C for temperatures in the calculations? Explain.

*Answer: 12.7 percent*

**6-121** Consider a Carnot heat-engine cycle executed in a closed system using 0.0103 kg of steam as the working fluid. It is known that the maximum absolute temperature in the cycle is twice the minimum absolute temperature, and the net work output of the cycle is 25 kJ. If the steam changes from saturated vapor to saturated liquid during heat rejection, determine the temperature of the steam during the heat rejection process.

**6-122**  Reconsider Prob. 6-121. Using EES (or other) software, investigate the effect of the net work output on the required temperature of the steam during the heat rejection process. Let the work output vary from 15 to 25 kJ.

**6-123** Consider a Carnot refrigeration cycle executed in a closed system in the saturated liquid–vapor mixture region using 0.96 kg of refrigerant-134a as the working fluid. It is known that the maximum absolute temperature in the cycle is 1.2 times the minimum absolute temperature, and the net work input to the cycle is 22 kJ. If the refrigerant changes from saturated vapor to saturated liquid during the heat rejection process, determine the minimum pressure in the cycle.

**6-124**  Reconsider Prob. 6-123. Using EES (or other) software, investigate the effect of the net work input on the minimum pressure. Let the work input vary from 10 to 30 kJ. Plot the minimum pressure in the refrigeration cycle as a function of net work input, and discuss the results.

**6-125** Consider two Carnot heat engines operating in series. The first engine receives heat from the reservoir at 1800 K and rejects the waste heat to another reservoir at temperature  $T$ . The second engine receives this energy rejected by the first one, converts some of it to work, and rejects the rest to a reservoir at 300 K. If the thermal efficiencies of both engines are the same, determine the temperature  $T$ . *Answer: 735 K*

**6-126** The COP of a refrigerator decreases as the temperature of the refrigerated space is decreased. That is, removing heat from a medium at a very low temperature will require a large work input. Determine the minimum work input required to remove 1 kJ of heat from liquid helium at 3 K when the outside temperature is 300 K. *Answer: 99 kJ*

**6-127E** A Carnot heat pump is used to heat and maintain a residential building at 75°F. An energy analysis of the house reveals that it loses heat at a rate of 2500 Btu/h per

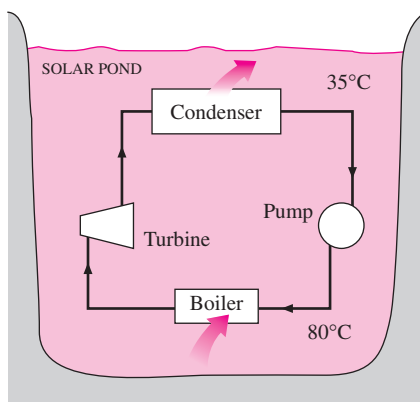


FIGURE P6-120

°F temperature difference between the indoors and the outdoors. For an outdoor temperature of 35°F, determine (a) the coefficient of performance and (b) the required power input to the heat pump. **Answers: (a) 13.4, (b) 2.93 hp**

**6-128** A Carnot heat engine receives heat at 750 K and rejects the waste heat to the environment at 300 K. The entire work output of the heat engine is used to drive a Carnot refrigerator that removes heat from the cooled space at  $-15^{\circ}\text{C}$  at a rate of 400 kJ/min and rejects it to the same environment at 300 K. Determine (a) the rate of heat supplied to the heat engine and (b) the total rate of heat rejection to the environment.

**6-129**  Reconsider Prob. 6-128. Using EES (or other) software, investigate the effects of the heat engine source temperature, the environment temperature, and the cooled space temperature on the required heat supply to the heat engine and the total rate of heat rejection to the environment. Let the source temperature vary from 500 to 1000 K, the environment temperature vary from 275 to 325 K, and the cooled space temperature vary from  $-20$  to  $0^{\circ}\text{C}$ . Plot the required heat supply against the source temperature for the cooled space temperature of  $-15^{\circ}\text{C}$  and environment temperatures of 275, 300, and 325 K, and discuss the results.

**6-130** A heat engine operates between two reservoirs at 800 and  $20^{\circ}\text{C}$ . One-half of the work output of the heat engine is used to drive a Carnot heat pump that removes heat from the cold surroundings at  $2^{\circ}\text{C}$  and transfers it to a house maintained at  $22^{\circ}\text{C}$ . If the house is losing heat at a rate of 62,000 kJ/h, determine the minimum rate of heat supply to the heat engine required to keep the house at  $22^{\circ}\text{C}$ .

**6-131** Consider a Carnot refrigeration cycle executed in a closed system in the saturated liquid–vapor mixture region using 0.8 kg of refrigerant-134a as the working fluid. The maximum and the minimum temperatures in the cycle are  $20^{\circ}\text{C}$  and  $-8^{\circ}\text{C}$ , respectively. It is known that the refrigerant is saturated liquid at the end of the heat rejection process, and the net work input to the cycle is 15 kJ. Determine the fraction of the mass of the refrigerant that vaporizes during the heat addition process, and the pressure at the end of the heat rejection process.

**6-132** Consider a Carnot heat-pump cycle executed in a steady-flow system in the saturated liquid–vapor mixture region using refrigerant-134a flowing at a rate of 0.264 kg/s as the working fluid. It is known that the maximum absolute temperature in the cycle is 1.25 times the minimum absolute temperature, and the net power input to the cycle is 7 kW. If the refrigerant changes from saturated vapor to saturated liquid during the heat rejection process, determine the ratio of the maximum to minimum pressures in the cycle.

**6-133** A Carnot heat engine is operating between a source at  $T_H$  and a sink at  $T_L$ . If it is desired to double the thermal efficiency of this engine, what should the new source temperature be? Assume the sink temperature is held constant.

**6-134** When discussing Carnot engines, it is assumed that the engine is in thermal equilibrium with the source and the sink during the heat addition and heat rejection processes, respectively. That is, it is assumed that  $T_H^* = T_H$  and  $T_L^* = T_L$  so that there is no external irreversibility. In that case, the thermal efficiency of the Carnot engine is  $\eta_C = 1 - T_L/T_H$ .

In reality, however, we must maintain a reasonable temperature difference between the two heat transfer media in order to have an acceptable heat transfer rate through a finite heat exchanger surface area. The heat transfer rates in that case can be expressed as

$$\dot{Q}_H = (hA)_H(T_H - T_H^*)$$

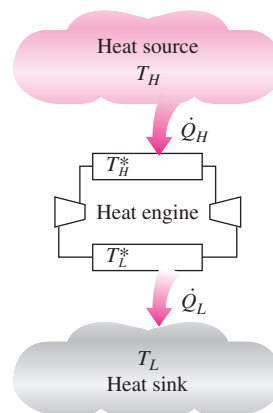
$$\dot{Q}_L = (hA)_L(T_L^* - T_L)$$

where  $h$  and  $A$  are the heat transfer coefficient and heat transfer surface area, respectively. When the values of  $h$ ,  $A$ ,  $T_H$ , and  $T_L$  are fixed, show that the power output will be a maximum when

$$\frac{T_L^*}{T_H^*} = \left(\frac{T_L}{T_H}\right)^{1/2}$$

Also, show that the maximum net power output in this case is

$$\dot{W}_{C,\max} = \frac{(hA)_H T_H}{1 + (hA)_H/(hA)_L} \left[ 1 - \left(\frac{T_L}{T_H}\right)^{1/2} \right]^2$$



**FIGURE P6-134**

**6-135** Replacing incandescent lights with energy-efficient fluorescent lights can reduce the lighting energy consumption to one-fourth of what it was before. The energy consumed by the lamps is eventually converted to heat, and thus switching to energy-efficient lighting also reduces the cooling load in summer but increases the heating load in winter. Consider a building that is heated by a natural gas furnace with an efficiency of 80 percent and cooled by an air conditioner with a COP of 3.5. If electricity costs \$0.08/kWh and natural gas costs \$1.40/therm, determine if efficient lighting will increase

or decrease the total energy cost of the building (a) in summer and (b) in winter.

**6-136** The cargo space of a refrigerated truck whose inner dimensions are  $12\text{ m} \times 2.3\text{ m} \times 3.5\text{ m}$  is to be precooled from  $25^\circ\text{C}$  to an average temperature of  $5^\circ\text{C}$ . The construction of the truck is such that a transmission heat gain occurs at a rate of  $80\text{ W}/^\circ\text{C}$ . If the ambient temperature is  $25^\circ\text{C}$ , determine how long it will take for a system with a refrigeration capacity of  $8\text{ kW}$  to precool this truck.

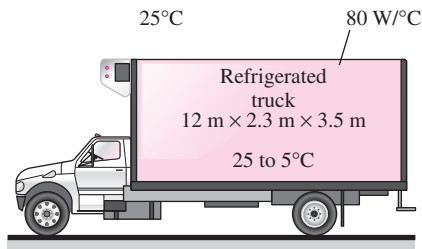


FIGURE P6-136

**6-137** A refrigeration system is to cool bread loaves with an average mass of  $450\text{ g}$  from  $22$  to  $-10^\circ\text{C}$  at a rate of  $500$  loaves per hour by refrigerated air at  $-30^\circ\text{C}$ . Taking the average specific and latent heats of bread to be  $2.93\text{ kJ/kg} \cdot ^\circ\text{C}$  and  $109.3\text{ kJ/kg}$ , respectively, determine (a) the rate of heat removal from the breads, in  $\text{kJ/h}$ ; (b) the required volume flow rate of air, in  $\text{m}^3/\text{h}$ , if the temperature rise of air is not to exceed  $8^\circ\text{C}$ ; and (c) the size of the compressor of the refrigeration system, in  $\text{kW}$ , for a COP of  $1.2$  for the refrigeration system.

**6-138** The drinking water needs of a production facility with  $20$  employees is to be met by a bubbler type water fountain. The refrigerated water fountain is to cool water from  $22$  to  $8^\circ\text{C}$  and supply cold water at a rate of  $0.4\text{ L}$  per hour per person. Heat is transferred to the reservoir from the surroundings at

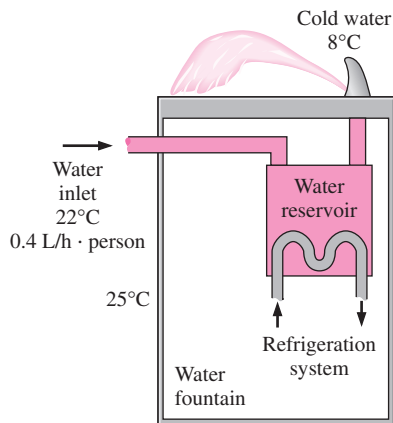


FIGURE P6-138

$25^\circ\text{C}$  at a rate of  $45\text{ W}$ . If the COP of the refrigeration system is  $2.9$ , determine the size of the compressor, in  $\text{W}$ , that will be suitable for the refrigeration system of this water cooler.

**6-139** The “Energy Guide” label on a washing machine indicates that the washer will use  $\$85$  worth of hot water per year if the water is heated by an electric water heater at an electricity rate of  $\$0.082/\text{kWh}$ . If the water is heated from  $12$  to  $55^\circ\text{C}$ , determine how many liters of hot water an average family uses per week. Disregard the electricity consumed by the washer, and take the efficiency of the electric water heater to be  $91$  percent.

**6-140E** The “Energy Guide” label on a washing machine indicates that the washer will use  $\$33$  worth of hot water if the water is heated by a gas water heater at a natural gas rate of  $\$1.21/\text{therm}$ . If the water is heated from  $60$  to  $130^\circ\text{F}$ , determine how many gallons of hot water an average family uses per week. Disregard the electricity consumed by the washer, and take the efficiency of the gas water heater to be  $58$  percent.

**6-141**  A typical electric water heater has an efficiency of  $90$  percent and costs  $\$390$  a year to operate at a unit cost of electricity of  $\$0.08/\text{kWh}$ . A typical heat pump-powered water heater has a COP of  $2.2$  but costs about



Water heater

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Jill Braaten, photographer

| Type                      | Efficiency |
|---------------------------|------------|
| Gas, conventional         | 55%        |
| Gas, high-efficiency      | 62%        |
| Electric, conventional    | 90%        |
| Electric, high-efficiency | 94%        |

FIGURE P6-141

\$800 more to install. Determine how many years it will take for the heat pump water heater to pay for its cost differential from the energy it saves.

**6-142**  Reconsider Prob. 6-141. Using EES (or other) software, investigate the effect of the heat pump COP on the yearly operation costs and the number of years required to break even. Let the COP vary from 2 to 5. Plot the payback period against the COP and discuss the results.

**6-143** A homeowner is trying to decide between a high-efficiency natural gas furnace with an efficiency of 97 percent and a ground-source heat pump with a COP of 3.5. The unit costs of electricity and natural gas are \$0.092/kWh and \$1.42/therm (1 therm = 105,500 kJ). Determine which system will have a lower energy cost.

**6-144** The maximum flow rate of a standard shower head is about 3.5 gpm (13.3 L/min) and can be reduced to 2.75 gpm (10.5 L/min) by switching to a low-flow shower head that is equipped with flow controllers. Consider a family of four, with each person taking a 6-minute shower every morning. City water at 15°C is heated to 55°C in an oil water heater whose efficiency is 65 percent and then tempered to 42°C by cold water at the T-elbow of the shower before being routed to the shower head. The price of heating oil is \$1.20/gal and its heating value is 146,300 kJ/gal. Assuming a constant specific heat of 4.18 kJ/kg · °C for water, determine the amount of oil and money saved per year by replacing the standard shower heads by the low-flow ones.

**6-145** The kitchen, bath, and other ventilation fans in a house should be used sparingly since these fans can discharge a houseful of warmed or cooled air in just one hour. Consider a 200-m<sup>2</sup> house whose ceiling height is 2.8 m. The house is heated by a 96 percent efficient gas heater and is maintained at 22°C and 92 kPa. If the unit cost of natural gas is \$1.20/therm (1 therm = 105,500 kJ), determine the cost of energy “vented out” by the fans in 1 h. Assume the average outdoor temperature during the heating season to be 5°C.

**6-146** Repeat Prob. 6-145 for the air-conditioning cost in a dry climate for an outdoor temperature of 28°C. Assume the COP of the air-conditioning system to be 2.3, and the unit cost of electricity to be \$0.10/kWh.

**6-147**  Using EES (or other) software, determine the maximum work that can be extracted from a pond containing 10<sup>5</sup> kg of water at 350 K when the temperature of the surroundings is 300 K. Notice that the temperature of water in the pond will be gradually decreasing as energy is extracted from it; therefore, the efficiency of the engine will be decreasing. Use temperature intervals of (a) 5 K, (b) 2 K, and (c) 1 K until the pond temperature drops to 300 K. Also solve this problem exactly by integration and compare the results.

**6-148** A heat pump with refrigerant-134a as the working fluid is used to keep a space at 25°C by absorbing heat from

geothermal water that enters the evaporator at 50°C at a rate of 0.065 kg/s and leaves at 40°C. Refrigerant enters the evaporator at 20°C with a quality of 15 percent and leaves at the same pressure as saturated vapor. If the compressor consumes 1.2 kW of power, determine (a) the mass flow rate of the refrigerant, (b) the rate of heat supply, (c) the COP, and (d) the minimum power input to the compressor for the same rate of heat supply. *Answers: (a) 0.0175 kg/s, (b) 3.92 kW, (c) 3.27, (d) 0.303 kW*

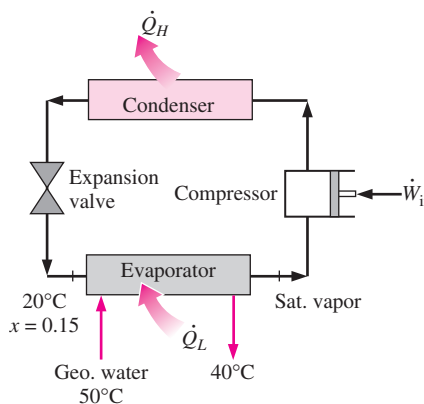


FIGURE P6-148

**6-149** Cold water at 10°C enters a water heater at the rate of 0.02 m<sup>3</sup>/min and leaves the water heater at 50°C. The water heater receives heat from a heat pump that receives heat from a heat source at 0°C.

(a) Assuming the water to be an incompressible liquid that does not change phase during heat addition, determine the rate of heat supplied to the water, in kJ/s.

(b) Assuming the water heater acts as a heat sink having an average temperature of 30°C, determine the minimum power supplied to the heat pump, in kW.

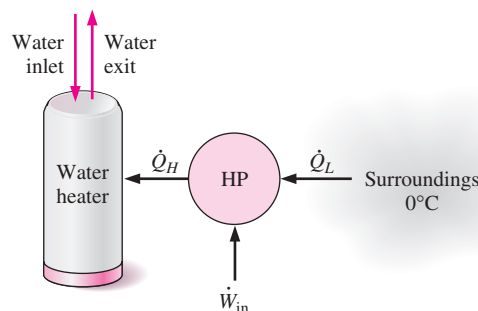


FIGURE P6-149

**6-150** A heat pump receives heat from a lake that has an average winter time temperature of 6°C and supplies heat into a house having an average temperature of 27°C.

(a) If the house loses heat to the atmosphere at the rate of 64,000 kJ/h, determine the minimum power supplied to the heat pump, in kW.

(b) A heat exchanger is used to transfer the energy from the lake water to the heat pump. If the lake water temperature decreases by 5°C as it flows through the lake water-to-heat pump heat exchanger, determine the minimum mass flow rate of lake water, in kg/s. Neglect the effect of the lake water pump.

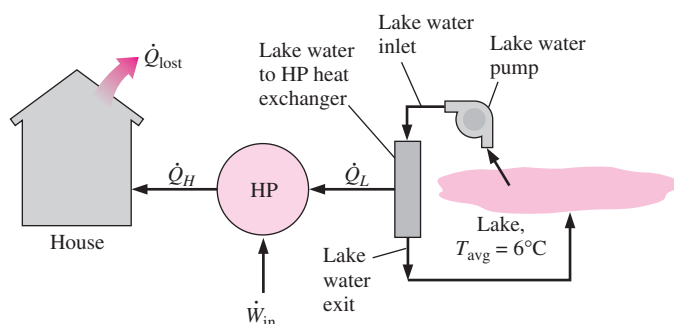


FIGURE P6-150

**6-151** A heat pump supplies heat energy to a house at the rate of 140,000 kJ/h when the house is maintained at 25°C. Over a period of one month, the heat pump operates for 100 hours to transfer energy from a heat source outside the house to inside the house. Consider a heat pump receiving heat from two different outside energy sources. In one application the heat pump receives heat from the outside air at 0°C. In a second application the heat pump receives heat from a lake having a water temperature of 10°C. If electricity costs \$0.085/kWh, determine the maximum money saved by using the lake water rather than the outside air as the outside energy source.

### Fundamentals of Engineering (FE) Exam Problems

**6-152** The label on a washing machine indicates that the washer will use \$85 worth of hot water if the water is heated by a 90 percent efficient electric heater at an electricity rate of \$0.09/kWh. If the water is heated from 15 to 55°C, the amount of hot water an average family uses per year is

- (a) 10.5 tons      (b) 20.3 tons      (c) 18.3 tons  
(d) 22.6 tons      (e) 24.8 tons

**6-153** A 2.4-m high 200-m<sup>2</sup> house is maintained at 22°C by an air-conditioning system whose COP is 3.2. It is estimated that the kitchen, bath, and other ventilating fans of the house discharge a houseful of conditioned air once every hour. If the average outdoor temperature is 32°C, the density of air is 1.20 kg/m<sup>3</sup>, and the unit cost of electricity is \$0.10/kWh, the amount of money “vented out” by the fans in 10 hours is

- (a) \$0.50      (b) \$1.60      (c) \$5.00  
(d) \$11.00      (e) \$16.00

**6-154** The drinking water needs of an office are met by cooling tap water in a refrigerated water fountain from 23 to 6°C at an average rate of 10 kg/h. If the COP of this refrigerator is 3.1, the required power input to this refrigerator is

- (a) 197 W      (b) 612 W      (c) 64 W  
(d) 109 W      (e) 403 W

**6-155** A heat pump is absorbing heat from the cold outdoors at 5°C and supplying heat to a house at 22°C at a rate of 18,000 kJ/h. If the power consumed by the heat pump is 2.5 kW, the coefficient of performance of the heat pump is

- (a) 0.5      (b) 1.0      (c) 2.0  
(d) 5.0      (e) 17.3

**6-156** A heat engine cycle is executed with steam in the saturation dome. The pressure of steam is 1 MPa during heat addition, and 0.4 MPa during heat rejection. The highest possible efficiency of this heat engine is

- (a) 8.0%      (b) 15.6%      (c) 20.2%  
(d) 79.8%      (e) 100%

**6-157** A heat engine receives heat from a source at 1000°C and rejects the waste heat to a sink at 50°C. If heat is supplied to this engine at a rate of 100 kJ/s, the maximum power this heat engine can produce is

- (a) 25.4 kW      (b) 55.4 kW      (c) 74.6 kW  
(d) 95.0 kW      (e) 100.0 kW

**6-158** A heat pump cycle is executed with R-134a under the saturation dome between the pressure limits of 1.8 and 0.2 MPa. The maximum coefficient of performance of this heat pump is

- (a) 1.1      (b) 3.6      (c) 5.0  
(d) 4.6      (e) 2.6

**6-159** A refrigeration cycle is executed with R-134a under the saturation dome between the pressure limits of 1.6 and 0.2 MPa. If the power consumption of the refrigerator is 3 kW, the maximum rate of heat removal from the cooled space of this refrigerator is

- (a) 0.45 kJ/s      (b) 0.78 kJ/s      (c) 3.0 kJ/s  
(d) 11.6 kJ/s      (e) 14.6 kJ/s

**6-160** A heat pump with a COP of 3.2 is used to heat a perfectly sealed house (no air leaks). The entire mass within the house (air, furniture, etc.) is equivalent to 1200 kg of air. When running, the heat pump consumes electric power at a rate of 5 kW. The temperature of the house was 7°C when the heat pump was turned on. If heat transfer through the envelope of the house (walls, roof, etc.) is negligible, the length of time the heat pump must run to raise the temperature of the entire contents of the house to 22°C is

- (a) 13.5 min      (b) 43.1 min      (c) 138 min  
(d) 18.8 min      (e) 808 min

**6-161** A heat engine cycle is executed with steam in the saturation dome between the pressure limits of 5 and 2 MPa.

If heat is supplied to the heat engine at a rate of 380 kJ/s, the maximum power output of this heat engine is

- (a) 36.5 kW                      (b) 74.2 kW                      (c) 186.2 kW  
(d) 343.5 kW                      (e) 380.0 kW

**6-162** An air-conditioning system operating on the reversed Carnot cycle is required to remove heat from the house at a rate of 32 kJ/s to maintain its temperature constant at 20°C. If the temperature of the outdoors is 35°C, the power required to operate this air-conditioning system is

- (a) 0.58 kW                      (b) 3.20 kW                      (c) 1.56 kW  
(d) 2.26 kW                      (e) 1.64 kW

**6-163** A refrigerator is removing heat from a cold medium at 3°C at a rate of 7200 kJ/h and rejecting the waste heat to a medium at 30°C. If the coefficient of performance of the refrigerator is 2, the power consumed by the refrigerator is

- (a) 0.1 kW                      (b) 0.5 kW                      (c) 1.0 kW  
(d) 2.0 kW                      (e) 5.0 kW

**6-164** Two Carnot heat engines are operating in series such that the heat sink of the first engine serves as the heat source of the second one. If the source temperature of the first engine is 1600 K and the sink temperature of the second engine is 300 K and the thermal efficiencies of both engines are the same, the temperature of the intermediate reservoir is

- (a) 950 K                      (b) 693 K                      (c) 860 K  
(d) 473 K                      (e) 758 K

**6-165** Consider a Carnot refrigerator and a Carnot heat pump operating between the same two thermal energy reservoirs. If the COP of the refrigerator is 3.4, the COP of the heat pump is

- (a) 1.7                      (b) 2.4                      (c) 3.4  
(d) 4.4                      (e) 5.0

**6-166** A typical new household refrigerator consumes about 680 kWh of electricity per year and has a coefficient of performance of 1.4. The amount of heat removed by this refrigerator from the refrigerated space per year is

- (a) 952 MJ/yr                      (b) 1749 MJ/yr                      (c) 2448 MJ/yr  
(d) 3427 MJ/yr                      (e) 4048 MJ/yr

**6-167** A window air conditioner that consumes 1 kW of electricity when running and has a coefficient of performance of 4 is placed in the middle of a room, and is plugged in. The rate of cooling or heating this air conditioner will provide to the air in the room when running is

- (a) 4 kJ/s, cooling    (b) 1 kJ/s, cooling    (c) 0.25 kJ/s, heating  
(d) 1 kJ/s, heating    (e) 4 kJ/s, heating

## Design and Essay Problems

**6-168** Devise a Carnot heat engine using steady-flow components, and describe how the Carnot cycle is executed in that engine. What happens when the directions of heat and work interactions are reversed?

**6-169** When was the concept of the heat pump conceived and by whom? When was the first heat pump built, and when were the heat pumps first mass-produced?

**6-170** Using a thermometer, measure the temperature of the main food compartment of your refrigerator, and check if it is between 1 and 4°C. Also, measure the temperature of the freezer compartment, and check if it is at the recommended value of -18°C.

**6-171** Using a timer (or watch) and a thermometer, conduct the following experiment to determine the rate of heat gain of your refrigerator. First make sure that the door of the refrigerator is not opened for at least a few hours so that steady operating conditions are established. Start the timer when the refrigerator stops running and measure the time  $\Delta t_1$  it stays off before it kicks in. Then measure the time  $\Delta t_2$  it stays on. Noting that the heat removed during  $\Delta t_2$  is equal to the heat gain of the refrigerator during  $\Delta t_1 + \Delta t_2$  and using the power consumed by the refrigerator when it is running, determine the average rate of heat gain for your refrigerator, in W. Take the COP (coefficient of performance) of your refrigerator to be 1.3 if it is not available.

**6-172** Design a hydrocooling unit that can cool fruits and vegetables from 30 to 5°C at a rate of 20,000 kg/h under the following conditions:

The unit will be of flood type, which will cool the products as they are conveyed into the channel filled with water. The products will be dropped into the channel filled with water at one end and be picked up at the other end. The channel can be as wide as 3 m and as high as 90 cm. The water is to be circulated and cooled by the evaporator section of a refrigeration system. The refrigerant temperature inside the coils is to be -2°C, and the water temperature is not to drop below 1°C and not to exceed 6°C.

Assuming reasonable values for the average product density, specific heat, and porosity (the fraction of air volume in a box), recommend reasonable values for (a) the water velocity through the channel and (b) the refrigeration capacity of the refrigeration system.